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This issue of Climate Matters highlights USGS research on Rocky Mountain ecosystems and their sensitivity to changing climate and land use, historic patterns of land use in the conterminous United States, and changes in seasonal wind patterns related to glaciation.

Science Partnerships

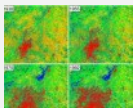


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New and Noteworthy

USGS Paleoclimate Research



We are pleased to announce the publication of a new paleoclimatology website designed to explain and exemplify the principles underlying paleoclimate science and highlight its importance to society.

Upcoming Meetings

The [2016 Annual Meeting of the Geological Society of America](#) will be held in Denver, Colorado from September 25 – 28, 2016. The GSA Annual Meeting brings together leaders and experts in the geosciences to advance the science and build new partnerships and collaborations.

The [Fall Meeting of the American Geophysical Union \(AGU\)](#) will be held from December 12-16, 2016 in San Francisco, California. The AGU Fall Meeting is the largest earth and space science meeting in the world.

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Debra Willard Managing Editor and Jack McGeehin Editor



About this issue

Mountain ecosystems in the western United States provide up to 85% of the water supply for humans in the region, as well as ecosystem services that include recreation, timber, and diverse plant and animal populations. The wide range of elevations in these mountains makes them particularly vulnerable to changing climate; seasonal changes in precipitation can affect the total snowpack, water supply, and potential for flooding or wildfires. In this issue, the Science Partnerships feature highlights recent research on long-term patterns of ecosystem variability in the Rocky Mountains that is being used to develop management strategies for the region.

The research featured in this newsletter is a sampling of the integrated science that the USGS Climate Research & Development Program conducts to improve our understanding of the rates, patterns, and consequences of climate and land use change. We welcome comments and feedback to shape future issues. If you would like to subscribe please click the “Subscribe” button on the Program Newsletter page.

Debra Willard

Coordinator, Climate Research & Development Program

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[Debra Willard](#) Managing Editor and [Jack McGeehin](#) Editor



Long-Term Collaborative Research Helps Rocky Mountain National Park Address Nitrogen-Based Air Pollution

Nitrogen is the most abundant element in the atmosphere. It is essential for life and is found in the amino acids, proteins, and genetic material of all living organisms. Nitrogen can also be a pollutant; it is a major cause of acid rain and dead zones in the world's oceans and large lakes.

Nitrogen comes in a number of chemical forms including nitrate, nitrite, and ammonium. It is emitted naturally from soils after bacterial processing, as well as from human sources, such as automobiles, industrial operations, and agriculture (Figure 1). All these emissions are transported through the atmosphere and interact with vegetation, soil, and water. Excessively high nitrogen levels in lakes and streams can change the composition and abundance of aquatic species and negatively affect ecosystem health and water quality. High-elevation catchments are particularly sensitive to small changes in the flux of nitrogen and can act as harbingers of ecosystem change at lower elevations.

Nitrogen deposition values and nitrate concentrations in a number of alpine and subalpine lakes within the Front Range of the Rocky Mountains are greater than those typically found in other remote, non-industrialized parts of the world. Atmospheric nitrogen deposition in the region not only exceeds pre-industrial deposition values, it has doubled since the mid-1900s. Current nitrogen concentrations exceed the requirements of many ecosystems, resulting in the export of excess nitrate into lakes and streams.

Rocky Mountain National Park (Rocky Mountain NP), located within the Front Range in north-central Colorado, contains over 107,000 hectares of montane forests, grasslands, glaciers, snowfields, lakes, and streams (Figure 2). More than half of Rocky Mountain NP is located at or above the tree line, which is the highest elevation at which trees can survive due to harsh weather conditions. For many years, natural resource managers have discussed the potential impacts of elevated nitrogen deposition and the need to develop air quality standards to protect these fragile, high-elevation ecosystems. In response to this concern, researchers from the U.S. Geological Survey Climate Research & Development Program (USGS) partnered with the U.S. National Park Service (NPS), Colorado State University (CSU), and the University of Colorado (CU) at Rocky Mountain NP to study watershed-scale

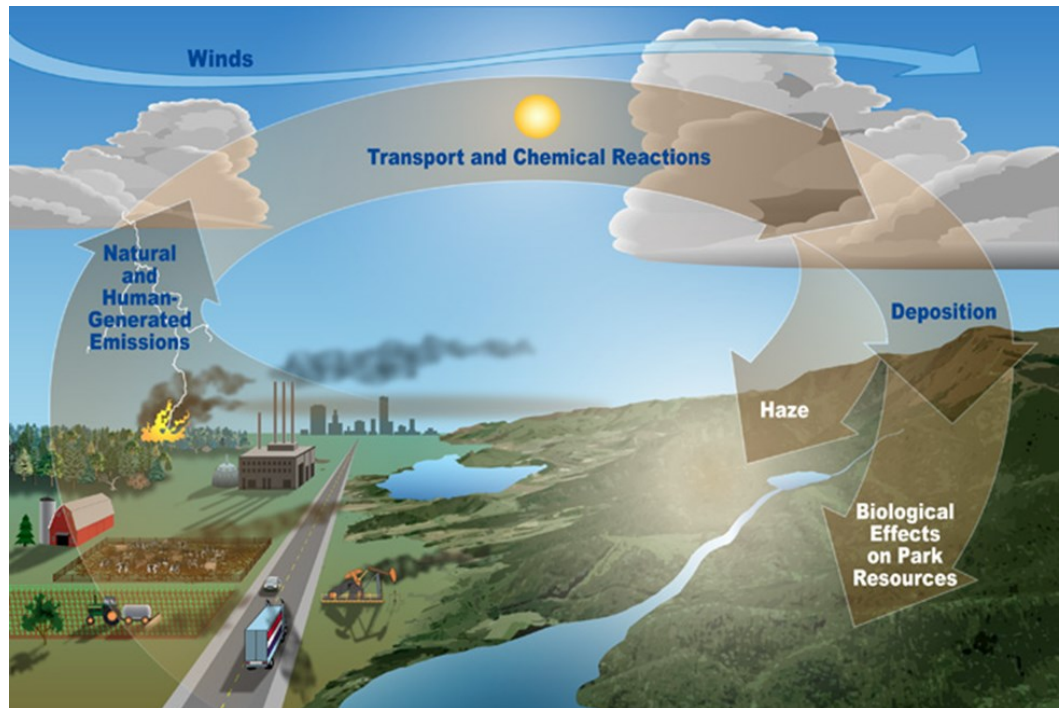


Figure 1. Nitrogen cycles continuously between the atmosphere, soil, and organisms. Nitrogen in the atmosphere and nitrogenous compounds in the soil are converted into substances that can be used by plants before being returned to the air and soil. Image courtesy of William Malm, National Park Service Air Resource Division.

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ecosystem processes, including nutrient cycling and water quality, and their responses to climate variability and atmospheric deposition.

The focal point of this cooperative research has been the Loch Vale watershed, located in Rocky Mountain NP (Figure 3). Loch Vale watershed is a high-elevation basin containing streams and four lakes within a narrow glaciated valley. Loch Vale drains 661 hectares of alpine and subalpine terrain, which are typical ecosystems in the Rocky Mountains. Only 6% of the watershed is forested, and the dominant tree species are Engelmann spruce and subalpine fir (Figure 4). Although the forests in Loch Vale have experienced natural disturbances including fire and avalanche, they have never been logged or settled. Researchers chose to focus on this small, pristine watershed because atmospheric and hydrologic inputs and outputs of nitrogen compounds and nutrients could be quantified.



Figure 2. The Loch, a glacial lake in Loch Vale watershed, Rocky Mountain National Park, Colorado. Photo credit: <http://www.fort.usgs.gov> (USGS).

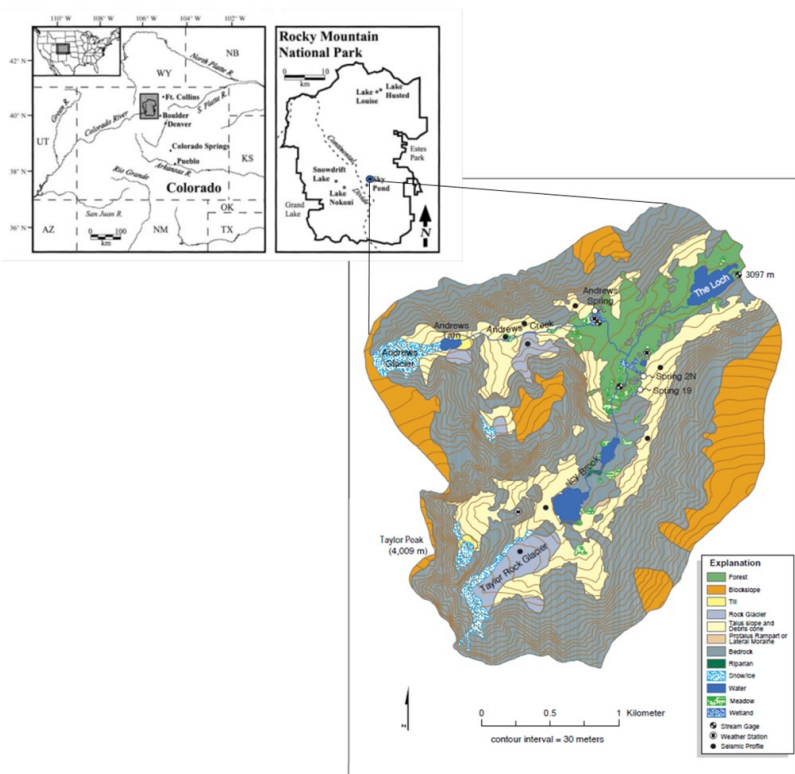


Figure 3. Map showing the location of Loch Vale watershed in Rocky Mountain National Park. Insert shows the locations of weather stations, stream gauges, monitoring springs, seismic profiles, and distribution of hydrogeologic units in Loch Vale (Modified from Clow *et al.* 2003, and Wolfe *et al.* 2003).

Using data on precipitation chemistry from the National Atmospheric Deposition Program (nadp.sws.uiuc.edu) and aquatic chemistry and stream flow data collected from tributaries and the outlet of Loch Vale, researchers developed a nitrogen budget for the watershed. Data collections extend as far back as 1982, providing insights on the variation in nitrogen concentration throughout the watershed and over time. Scientists also measured isotopic and chemical tracers of oxygen and nitrogen content from various water sources, including snowpack, snowmelt, rain, and surface and ground water to determine the origin of nitrogen exported by the streams (Figure 4). Results showed that atmospheric deposition was the primary source of nitrate to the watershed.

The research also shed light on how nitrogen from atmospheric deposition is cycled through ecosystems. Climate extremes, lake primary productivity, and microbial activity all play a role in the retention and release of nitrogen in the system. Additionally, USGS, CSU, and CU researchers documented changes in the species composition and concentration of algal primary producers ([diatoms](#)) in high elevation lakes in Loch Vale. Since AD circa 1950-1960, diatom species indicative of nitrogen enrichment increased significantly. Plant and soil communities in high-elevation Rocky Mountain ecosystems were also found to be affected by slight increases in nitrogen availability. Increased nitrogen deposition corresponded to changes in tundra plant community

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Figure 4. Researcher cores through the ice to obtain water samples from the Loch. These samples are used to measure lake chemistry in the winter. Photo credit: <http://co.water.usgs.gov/lochvale> (USGS).

composition, increased soil microbial activity, and elevated nitrogen concentrations in the needles of old-growth spruce forests in the region. Together, these studies gave Rocky Mountain NP managers a large body of evidence on sources of nitrogen deposition to the park, the ecological effects of nitrogen on susceptible ecosystems, and pathways of nitrogen cycling.

One of the most influential outcomes of this research program was its determination of critical nitrogen loads to the catchment. A critical nitrogen load is the amount of nitrogen necessary to cause harmful effects to sensitive organisms and the ecosystem. Using these USGS-generated estimates on critical nitrogen loads as a foundation, the National Park Service, the Colorado Department of Public Health and Environment and the U.S. Environmental Protection Agency (EPA) worked collaboratively to develop and implement a plan that would focus on reducing nitrogen emissions and deposition in the park. The [Nitrogen Deposition Reduction Plan for Rocky Mountain National Park](#), released in 2007, described emissions, transport, sources, and trends of atmospheric deposition of nitrogen to Rocky Mountain NP. The plan also outlined a 25-year management strategy to reduce emissions so that deposition would fall below critical nitrogen loads.

The plan targets reduced loads and achievable goals by 2032, with milestones for nitrogen reduction set every five years. Local farmers, ranchers, dairy owners, the state of Colorado, the EPA, and the NPS have all come together to discuss best management practices outlined in the plan and determine strategies for voluntary nitrogen emissions reductions in the region.

The issues described here are not exclusive to Rocky Mountain NP; increased atmospheric deposition of pollutants affects ecosystems at other national parks, especially in the eastern United States. Data from these collaborations have implications for ongoing efforts to protect parks and natural areas from air pollution across the country. Other national parks and resource managers are watching to see what strategies can be developed, what goals are achieved, and what can be learned from these efforts.

The unique aspect of this working group is the alliance among stakeholders. Rocky Mountain NP is one of the first parks in the country where such a large group of private business owners and government researchers have come together to reduce nutrient loads voluntarily for the health of the ecosystem, cleaner water, and improved air quality in the region.

For more information, contact [Nicole Cormier](#).

Further readings:

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Evidence for seasonal controls on the transportation of loess in Matanuska Valley, southern Alaska

Loess is windblown silt. It is an important surficial deposit that can be centimeters to tens of meters thick, and it forms the parent material for soils on many continents. During the last glacial period, about 25,000-12,000 years ago, loess was deposited over wide areas of midcontinental North America, Alaska, Asia, Europe and South America.

Because it is deposited directly by the wind and preserved in place, spatial changes in loess thickness and grain size characteristics can provide important information about past wind directions that can aid our understanding of past atmospheric circulation. In regions such as the midcontinent of North America, however, what is not well understood is the seasonal timing of loess deposition.

Loess is derived largely from continental glaciers that are no longer found in North America; thus, analogs must be sought in places where glaciers occur today, such as Alaska. Loess is a widespread surficial deposit in Alaska, and loess accretion occurs today in some regions, such as the Matanuska Valley.

The source of loess in the Matanuska Valley has been debated for more than seven decades, with the Knik River and the Matanuska River, both to the east of the Valley, being the leading candidates and the Susitna River, to the west of the Valley, as a less favorable source.

USGS researchers, in a newly published paper, report new stratigraphic, mineralogical, and geochemical data that test the competing hypotheses of these river sources. Loess stratigraphic data are consistent with previous studies that show that a source or sources lay to the east of the Matanuska Valley, which rules out the Susitna River. Knik and Matanuska River silts can be distinguished using geochemical “fingerprints” that match the silt in a loess deposit with its source material. Using these geochemical tools, the researchers determined that Matanuska Valley loess falls clearly within the range of values found in Matanuska River silt.

Dust storms from the Matanuska River are most common in autumn, when river discharge is at a minimum and silt-rich point bars are exposed, wind speed from the north is beginning to increase after a low-velocity period in summer, snow depth is still minimal, and soil temperatures are still above freezing. Thus, seasonal changes in climate and hydrology emerge as critical factors in the timing of windblown silt transport and loess accretion in southern Alaska.

These findings could be applicable to understanding seasonal controls on last-glacial-age loess accretion in Europe, Asia, South America, and midcontinental North America.

The paper, “*Geochemical evidence for seasonal controls on the transportation of Holocene loess, Matanuska Valley, southern Alaska, USA*”, was published in *Aeolian Research*. It is available at <http://www.sciencedirect.com/science/article/pii/S1875963715300136>



The Matanuska River, southern Alaska, at a time of low discharge in autumn, with silt-rich point bars exposed, adjacent cliff-top loess and wind-blown sand (on the left), and the Talkeetna Mountains in the background.

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Modeled Historical Land Use and Land Cover for the Conterminous United States

The landscape of the conterminous United States has changed dramatically since the start of the 20th century, with agriculture, urban expansion, forestry, and other anthropogenic land uses altering the land's surface across vast swaths of the country. Landscape change has direct effects on many natural processes, including carbon and biogeochemical cycles, hydrology, biodiversity, and climate. Understanding how the landscape has changed in the past helps scientists to understand what the impacts were on climate, ecological and societal processes, and it informs efforts to mitigate any potential negative impacts of landscape change in the future.

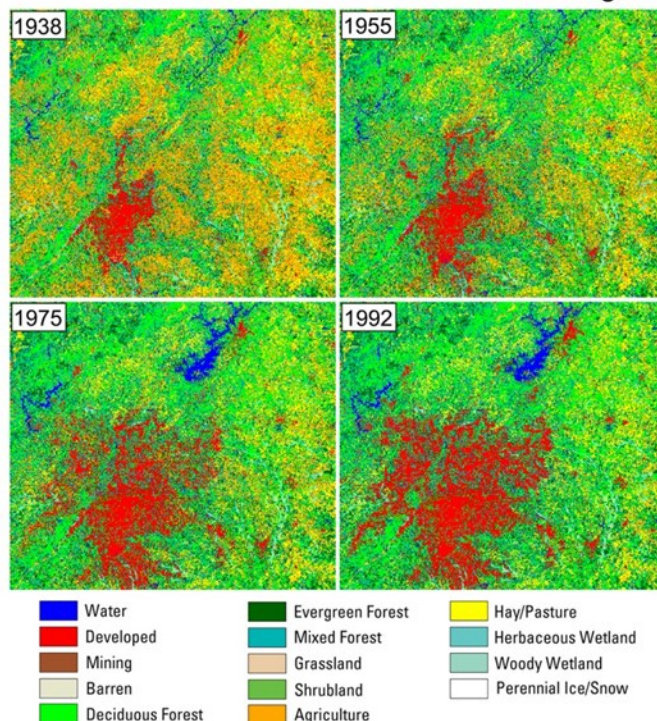
Consistent, regional- to global-scale satellite observations began in 1972 with the launch of Landsat 1 (originally named Earth Resources Technology Satellite 1). The first maps of historical landscape change based on these data were not created until 1992, and the only prior LULC mapping for the United States is a 1970s era map created by the USGS using an interpretation of aerial photography. Modeling approaches are often used to produce projections of future landscape change, but these methodologies have rarely been used to model and reconstruct historical landscapes. To fill the need for consistent, thematically and spatially detailed maps of historical LULC change, the USGS used a modeling approach to create historical annual maps for the conterminous United States going back to 1938.

The modeling of historical landscape change was based on well-quantified historical data sources documenting anthropogenic land-use change, including satellite-based landscape observations going back to 1973, databases on historical changes in agricultural land use and extent, population and urban change, wetland loss, reservoir construction dates, and other historical data sources. The USGS' Forecasting Scenarios of Land-use Change (FORE-SCE) model was used to create spatially explicit historical maps from 1938 to 1992 for the conterminous U.S. at a 250-meter spatial resolution, representing 14 thematic classes (see figure for example).

These data represent the first spatially explicit, thematically detailed LULC data available for the entire conterminous United States for dates prior to availability of data from the Landsat series of satellites. The results closely mimic rates of changes measured by numerous historical data sources. Researchers can use LULC data from this historical period to reveal connections between LULC change and a variety of ecological and societal phenomenon. Additionally, this data can be used in combination with a previously produced suite of landscape projections from 1992 through 2100, to better understand the potential future consequences of LULC change.

The modeled historical data from this study, as well as multiple projections of future landscape change, are freely available for download and use at <http://landcover-modeling.cr.usgs.gov/>. The paper, *Modeled historical land use and land cover for the conterminous United States*, was published in the Journal of Land Use Science. It is available at: <http://www.tandfonline.com/doi/full/10.1080/1747423X.2016.1147619>

Modeled Historical Land Cover - Atlanta Region



Modeled historical land cover near Atlanta, Georgia. Widespread loss of agricultural land, an increase in urbanized area, and the construction of reservoirs occurred between 1938 and 1992. (Credit: T. Sohl, USGS EROS)

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Tracking long-term changes in Rocky Mountain Snowpack

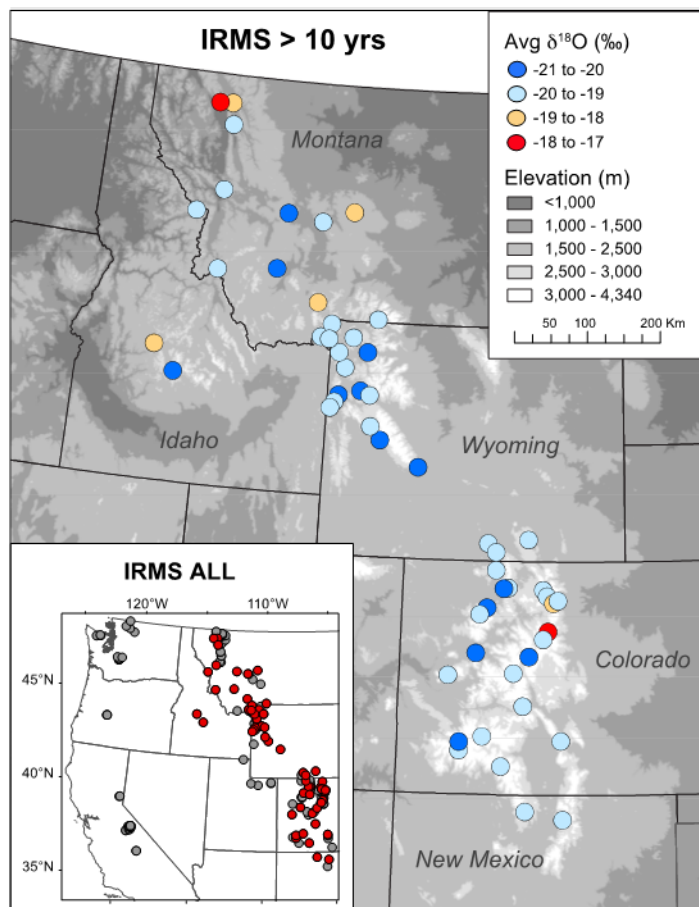
Changes in Rocky Mountain snow is a leading stressor on alpine ecosystems and the communities that depend on the water resources that snowpack provides. As the region is faced with increasing water demands from a growing population, effective future planning will be assisted by a better understanding of how future climate change, based on long-term projections, will affect future snowpack. Scientists are conducting research to provide new insights on how snowpack may evolve in the future, using observations of the present and long-term records of the past.

Estimates of past snow and rain precipitation amounts can be made from the geochemical signatures within sediments deposited in lakes during the past 11,000 years. One signature, isotope ratios, compares the abundance of two oxygen isotopes (^{18}O and ^{16}O). In precipitation, the temperature, humidity and history of water vapor movement in the atmosphere control relative isotope abundances. The oxygen isotope ratios at a given time are preserved in geologic materials that span long periods of time including, ice cores, tree rings, corals, soils and cave deposits, such as speleothems and can be measured in incremental samples to generate continuous records of past oxygen isotope ratios. Interpretations of oxygen isotope ratios from geologic archives are largely based upon comparisons between modern depositional environments and simultaneously observed meteorology and climatology.

For environments where snowfall accounts for the majority of annual precipitation, snowmelt, rather than precipitation, is likely to have the strongest influence on isotopic values contained within geologic materials. Although climate patterns affect snowpack amount and duration, scientists have lacked the modern measurements of snowpack isotope ratios to compare with climate variables that are needed to interpret past climate from geologic materials. To address this uncertainty, USGS scientists and academic colleagues made ~1300 oxygen isotope measurements of snowpack from a network of ~60 sites in the Rocky Mountains for a 20 year period beginning in 1993. The network, known as the Isotopes in Rocky Mountain Snowpack (IRMS) network, provides the most extensive documentation of snowpack isotope values outside of Polar Regions.

The results of this study provide new understanding of the processes that influence snowpack oxygen isotope ratios. Isotopic values in snowpack are rarely controlled by temperature alone but also reflect additional atmospheric processes that alter storm track orientations and moisture sources. Other processes that occur after snow accumulation such as evaporation and sublimation also cause a great deal of spatial and temporal differences. To address these complexities, scientists identified regionally representative locations with the most consistent climate-isotope patterns to improve their abilities to use oxygen isotope ratios to define past climate estimates and their uncertainty.

Knowledge of Rocky Mountain snowpack responses to climate variability is critical for understanding long-term patterns of



Sampling locations for the Isotopes in Rocky Mountain Snowpack (IRMS) Network shown on a gray shaded DEM. Color scale indicates average snowpack $\delta^{18}\text{O}$ for 57 locations with >10 years of data (in red on the inset, which shows all 177 IRMS locations).

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snowfall, water availability and quality, as well as their response to different climate and environmental stressors. Improved capabilities, such as those that the IRMS network can provide, to accurately document pre-historic snowpack fluctuations provides past analogues for potential future climate scenarios to better inform water resource planning.

The paper, *Isotopes in North American Rocky Mountain Snowpack 1993-2014*, was published in Quaternary Science Reviews. It is available at <http://www.sciencedirect.com/science/article/pii/S0277379115001304>.



Photo credit George Ingersoll. For further information on the USGS Rocky Mountain Snowpack sites: http://co.water.usgs.gov/projects/RM_snowpack/

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Meltwater Characteristics Of Western Mountain Glaciers and Rock Glaciers

Glaciers and rock glaciers (coarse rock fragments bound together and lubricated by ice) are melting worldwide from climate change, mobilizing ice-locked organic matter, minerals, and nutrients. The release of these meltwater constituents has implications for downstream chemical cycling and biological activity. Past studies have found that headwater alpine lakes and streams fed by glaciers have higher nutrient concentrations than headwaters fed only by snow. In a new USGS study, researchers were able to extend this finding by showing that different types of glaciers differ in their biogeochemical contributions. The results suggest that different types of glaciers affect their local ecosystems and have the potential to alter fundamental ecological aspects in important headwater ecosystems.

Not all glaciers are created equal. This study compared the different meltwater compositions of ice glaciers and rock glaciers in the western U.S. and asked whether there were differences in physical, chemical and microbial characteristics in meltwater. An extensive field sampling effort over three summers of 25 alpine glaciers and 24 rock glaciers found in the Cascades, Sierra Nevada, and Rocky Mountains provided the data for comparison.



There were clear differences between the meltwater compositions of glaciers and rock glaciers, and there were also geographic differences. The type of glacier (ice or rock) influences the downstream concentration of weathering products such as silica, calcium, and strontium. Glacier type also affected the complexity of organic matter exported via meltwaters, with glaciers producing organic matter that appears to originate as a byproduct of microbes and rock glaciers providing organic matter from plant decomposition as well as microbes. The geology of each mountain range controls the chemistry of the weathering products released; geology and climate influences the rate and intensity of weathering. The location of the glaciers relative to human settlement affects the compounds found in ice that come from atmospheric deposition. For example, while rock glaciers produced more nitrate than glaciers at all sample sites, the nitrate concentrations in the Rocky Mountain samples were very high because of proximity to agricultural and metropolitan sources of nitrogen. Unexpectedly, both the type of glacier and geographic location influence microbial diversity. The greatest microbial diversity was in rock glaciers, but there were many microbes that were found both in rock and ice glaciers. The Rocky Mountains had higher microbial diversity than the Cascades, but there were common microbes across all the mountains.

Glaciers and rock glaciers sit at the interface of atmospheric and terrestrial environments, where inputs are captured, stored, altered, and then released to alpine headwaters. With 10,000 rock glaciers identified in the U.S., they are five times more common than ice glaciers. In coming centuries, rising temperatures will melt rock glaciers and ice glaciers alike. Some, ice glaciers may become rock glaciers as they shrink. Because rocks insulate rock glaciers, they melt more slowly, and will likely exist after ice glaciers disappear. Knowing the meltwater composition of both glaciers and rock glaciers will help predict how they will alter downstream ecosystems in the future.

The paper, *The Differing Biogeochemical and Microbial Signatures of Glaciers and Rock Glaciers*, was published in JGR-Biosciences. It is available at <http://onlinelibrary.wiley.com/doi/10.1002/2015JG003236/full>.

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